ICRA 2007 Space Robotics Workshop

SILVRCLAW

(Stowable, Inflatable, Vectran, Rigidizable, Cold-resistant, Lightweight, All-terrain Wheel)

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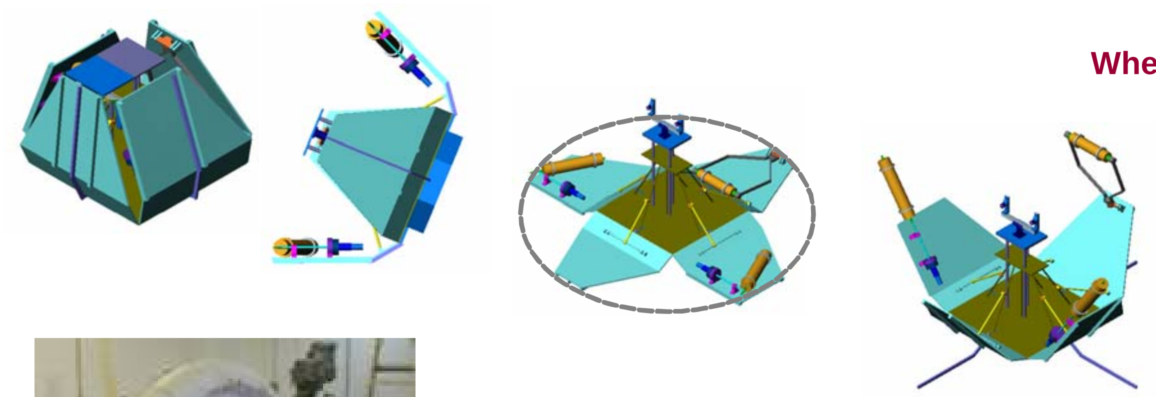
Rome, Italy

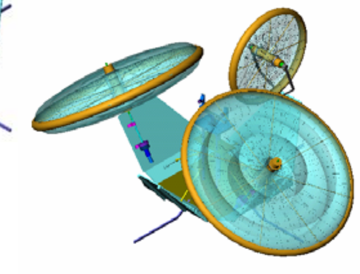
Overview

- SILVRCLAW Concept
- Motivation for SILVRCLAW Technology
- Modeling
- Material Testing
- Prototype Development
- Testbed
- Prototype Testing
- Upgrades and Environmental Testing
- Summary of Results and Conclusions

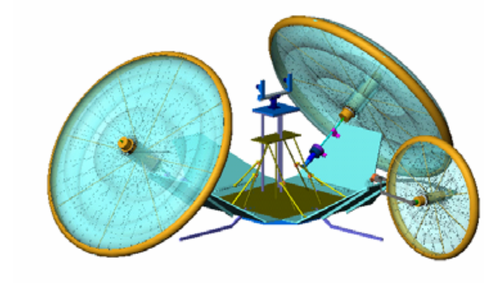
SILVRCLAW Concept



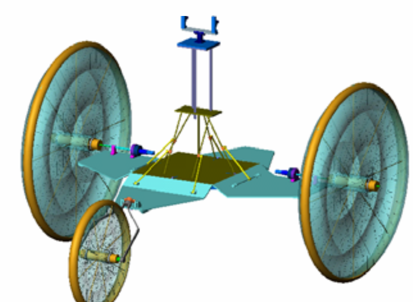
Wheel inflates



Composite rim rigidizes through a melt process

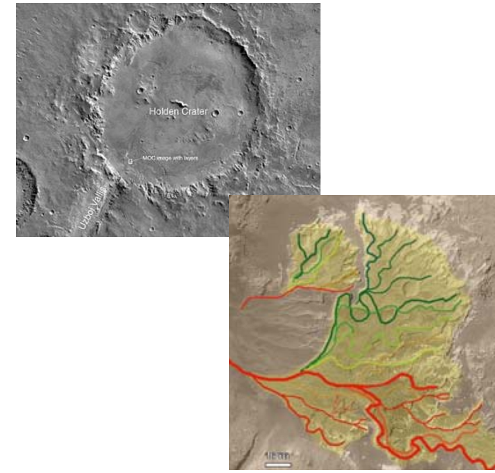


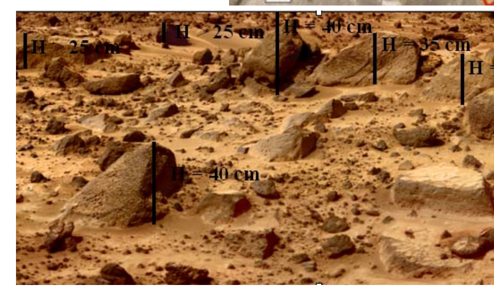
Flexible spokes are pretensioned during rim rigidization



Mars Regional Mobility Requirements

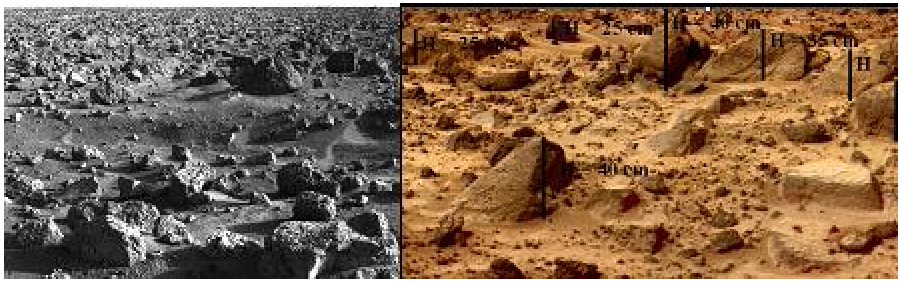
- **Mars terrain accessibility and technical goals:**
  - Provide the ability to access terrains (i.e. fluvial fans, steep sedimentary terrains, Mars polar layered terrains, polar caps, …) that are of particular astrobiologic and general scientific interest and are not readily accessible with lower ground clearance vehicles.
  - Provide cabability to deploy wheels up to 1.5m diameter for providing low surface hazard density (<1 hazard per 100m) and enable potential for surface waypoint placement from orbit (i.e. with MRO's Highrise 30cm/pixel resolution). Provide ability to package wheels into <3.5m aeroshell
  - Increase the load carrying capacity to >100 kg/wheel in Mars g-field (10-100 fold increase over basic inflatables) with a ~10kg mass allocation to wheel (>10:1 load carrying capacity).
  - Increase the overall range of a 100's kg rover to >100km within <1 year timeframes with power consumption of <100 Whr/km and <100 Whr/sol (enables alternative low power architectures like small RPS).
  - Use deployment technology that requires no sustained gas pressure over duration of wheel operation (remove special material requirements for flexible membranes over low temperature thermal cycling and abrasive environments

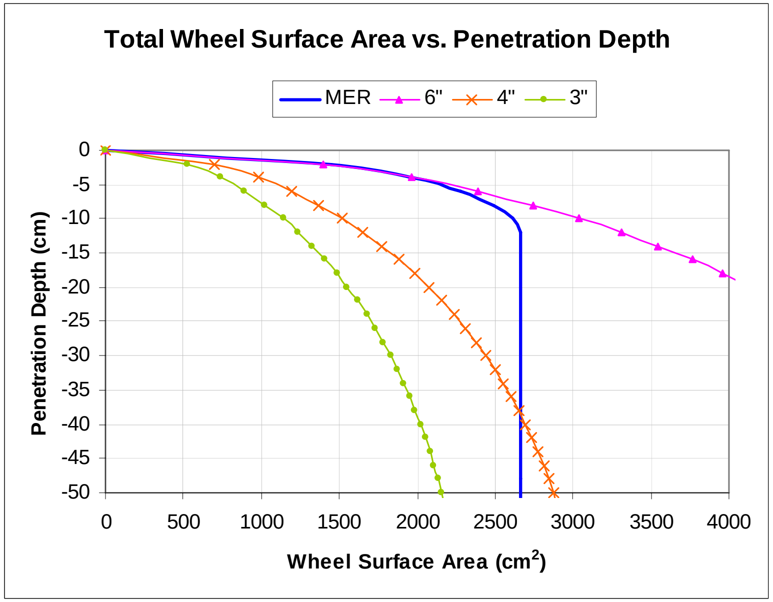


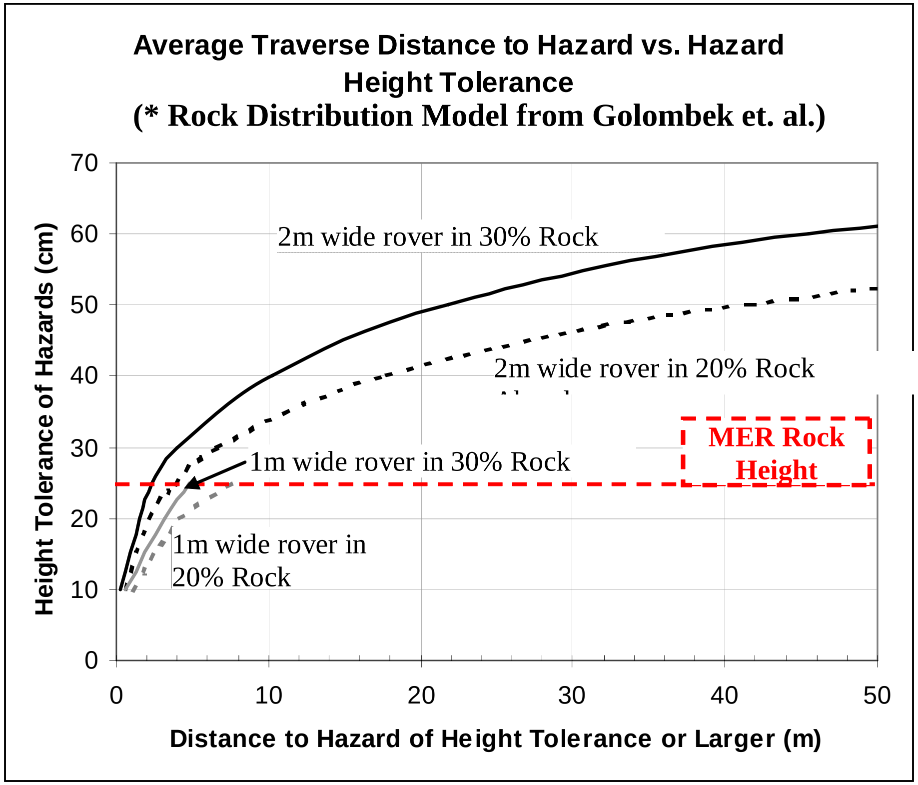


Wheel Sizing

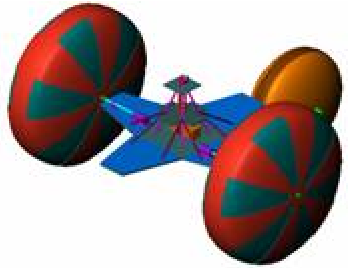
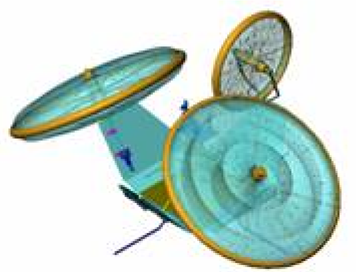
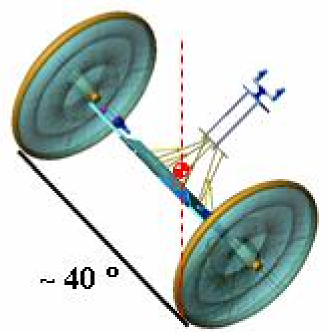
- **Identify geometry requirements for a large diameter deployable wheel**
  - 1.3-1.5m diameter specified based on ground clearance estimates, orbital imaging resolution (MRO's 30cm/pixel), drive power estimates, and some tolerance to manufacturing
  - Initial 6" (15cm) wide rim selected based on 1st order equivalent footprint sinkage rates relative to MER wheel profiles



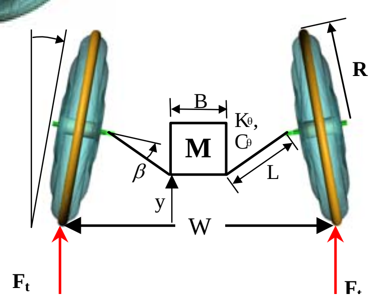


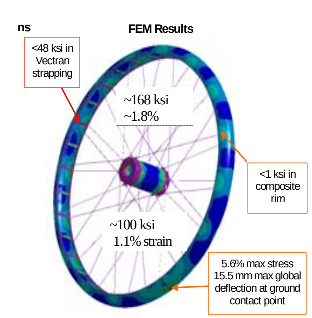


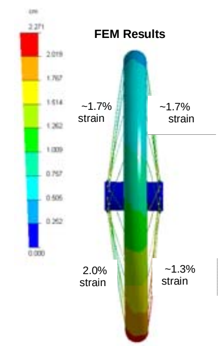
SILVRCLAW Configuration Design

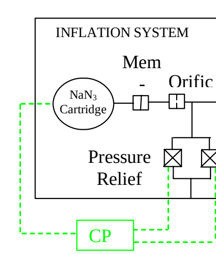




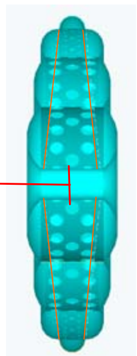
- **Populated trade space with candidate wheel deployment concepts and possible vehicle geometries**
- **Evaluated wheel concepts for deployment complexity, resultant wheel mechanics, and wheel material characteristics in operating environment**
  - Deployed wheel structural properties (static and dynamic), material brittle transition properties, non-linear structural effects (i.e. creep resistance), terramechanics (load bearing capacity, drive power consumption), deployment requirements (inflation, curing, and heating requirements in Mars thermal environment), vehicle stability.
- **Evaluated SILVRCLAW material properties at coupon level (iterative through development)**





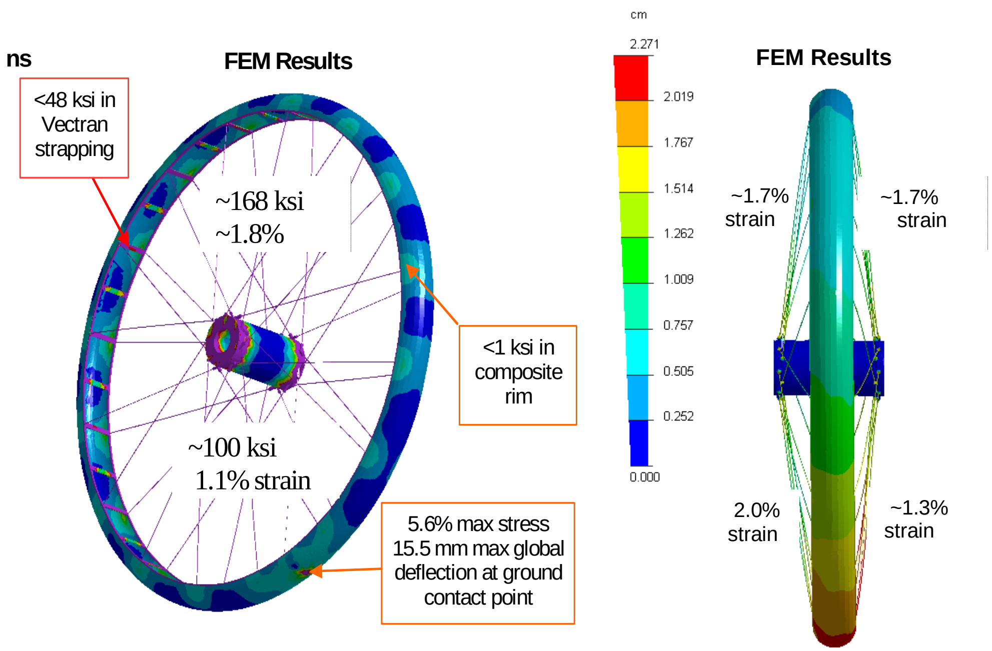






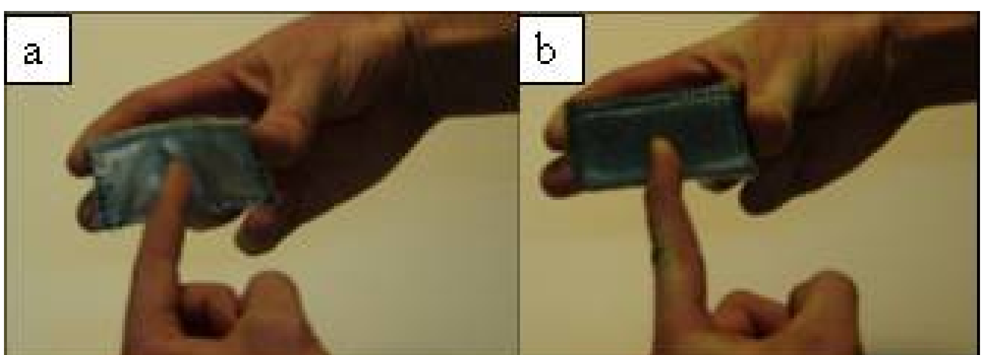
SILVRCLAW Modeling

- **Wheel structural analysis (FEM analysis, spoke deployment strain relaxation post deflation, dynamic analysis)**
- **Terramechanics analysis (soil sinkage, traverse power consumption - see testbed slides for comparison w/ experiment)**



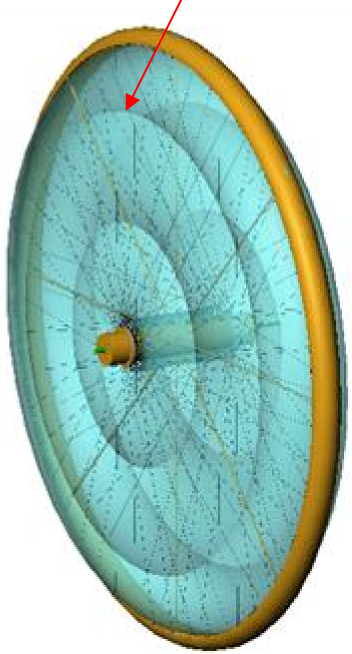
SILVRCLAW Material Testing

- **Tested material properties and downselected to material providing F.S. of >7 over initial contact load failure stress with 180kg wheel rover in 1m Mars fall**
- **Since then testbed tests indicate wheel design is likely driven by localized buckling failure stresses with cleat contact loads rather than global rim structural**
- **Theoretical brittle transition temperature ~ –70°C**

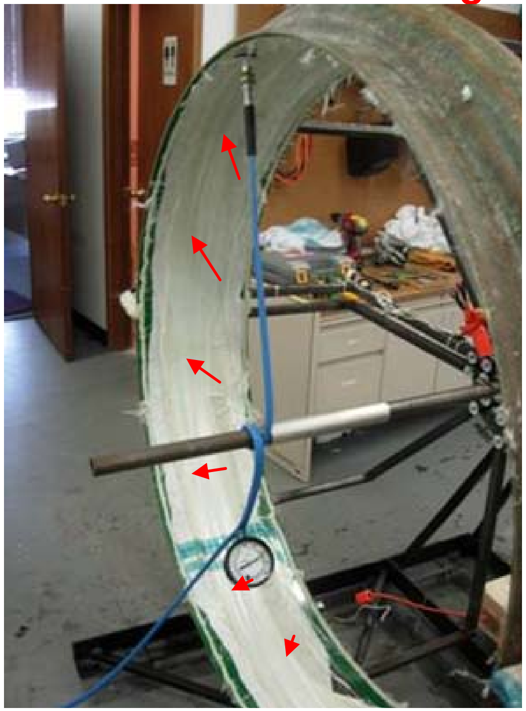


Prototype SILVRCLAW Exoskeleton

Positive Pressure Inflation Bag for Future Deployment



Simulated Positive Pressure Rim Cure and Heating



1st SILVRCLAW Wheel (8.9kg Overdesigned Rim + Spokes)

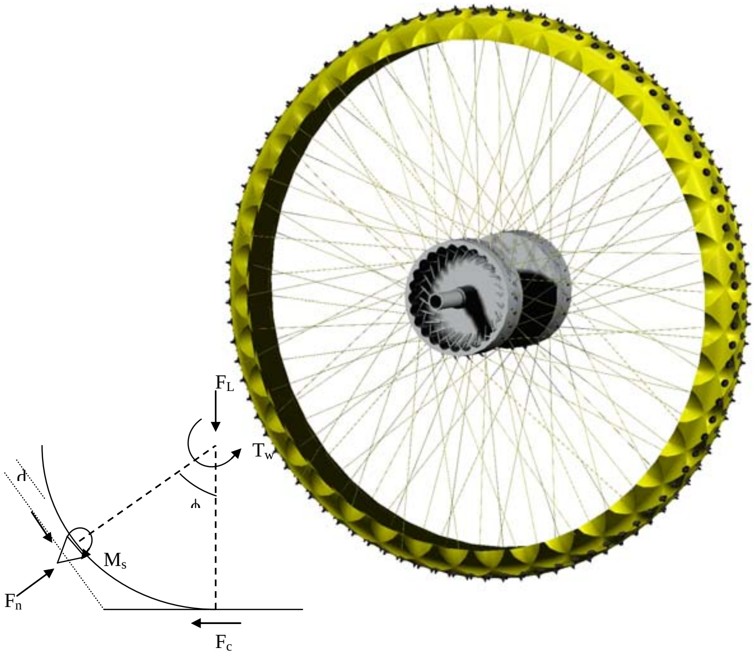
SILVRCLAW Exoskeleton Development

- **Developed exoskeleton of SILVRCLAW wheel with identified materials. Perform initial static tests (load and creep)**
- **Iterated and upgraded exoskeleton design (e.g. tread and spokes) based on results of testbed testing (see following slide)**

Sheathed Spoke

Prototype I Spoke Testing

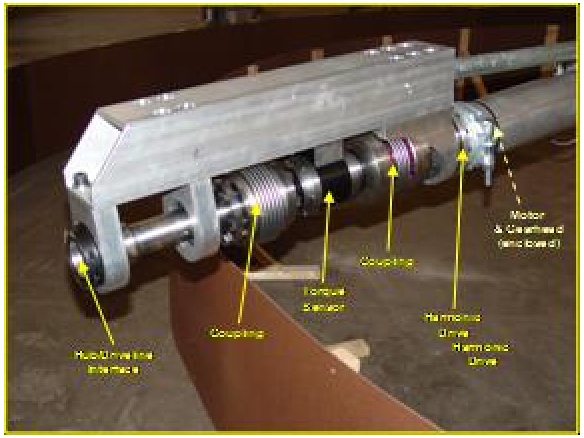
Cleated Wheel Design

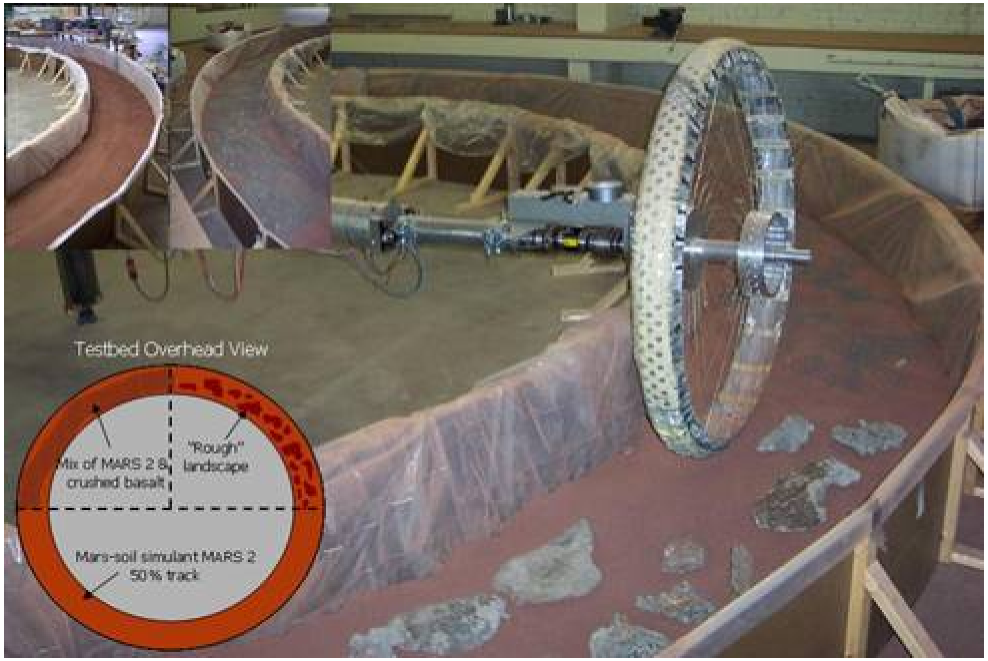


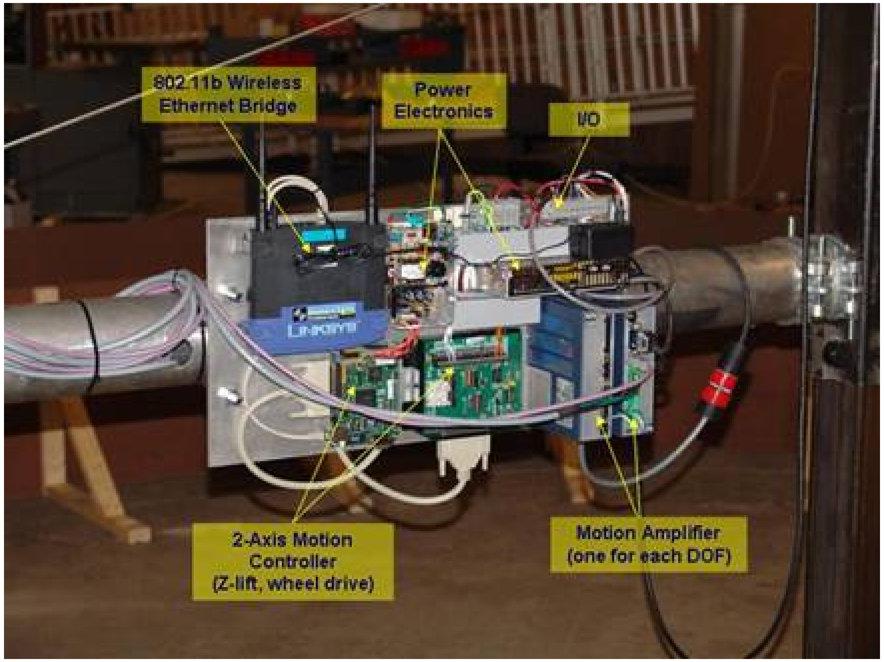
Cleated Exoskeleton

Wheel Robotic Testbed Development

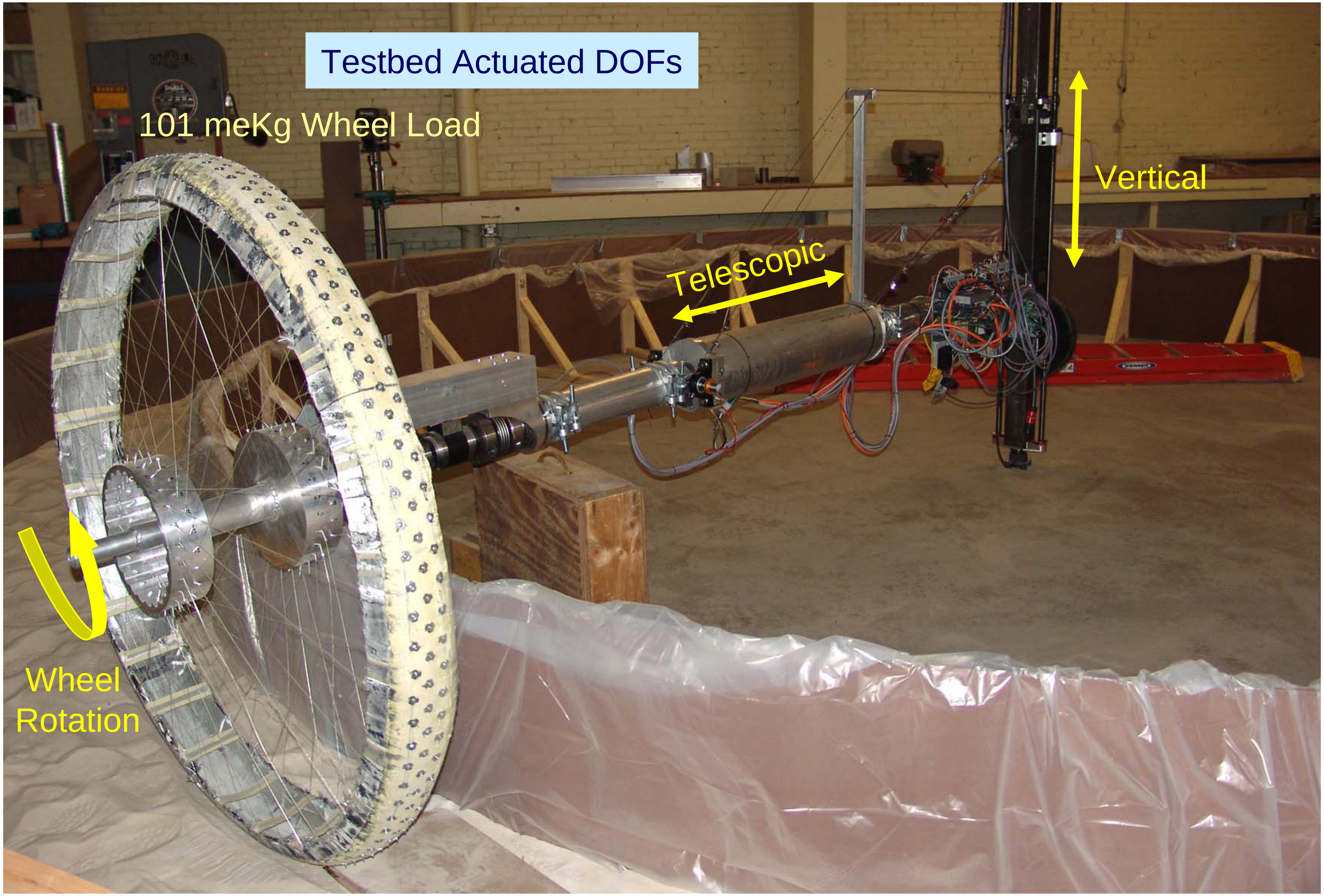
- **Circular testbed for mobility testing**
- **Realistic soils simulants and rock types & distribution**
- **Testbed setup to accommodate variable loading & controls**



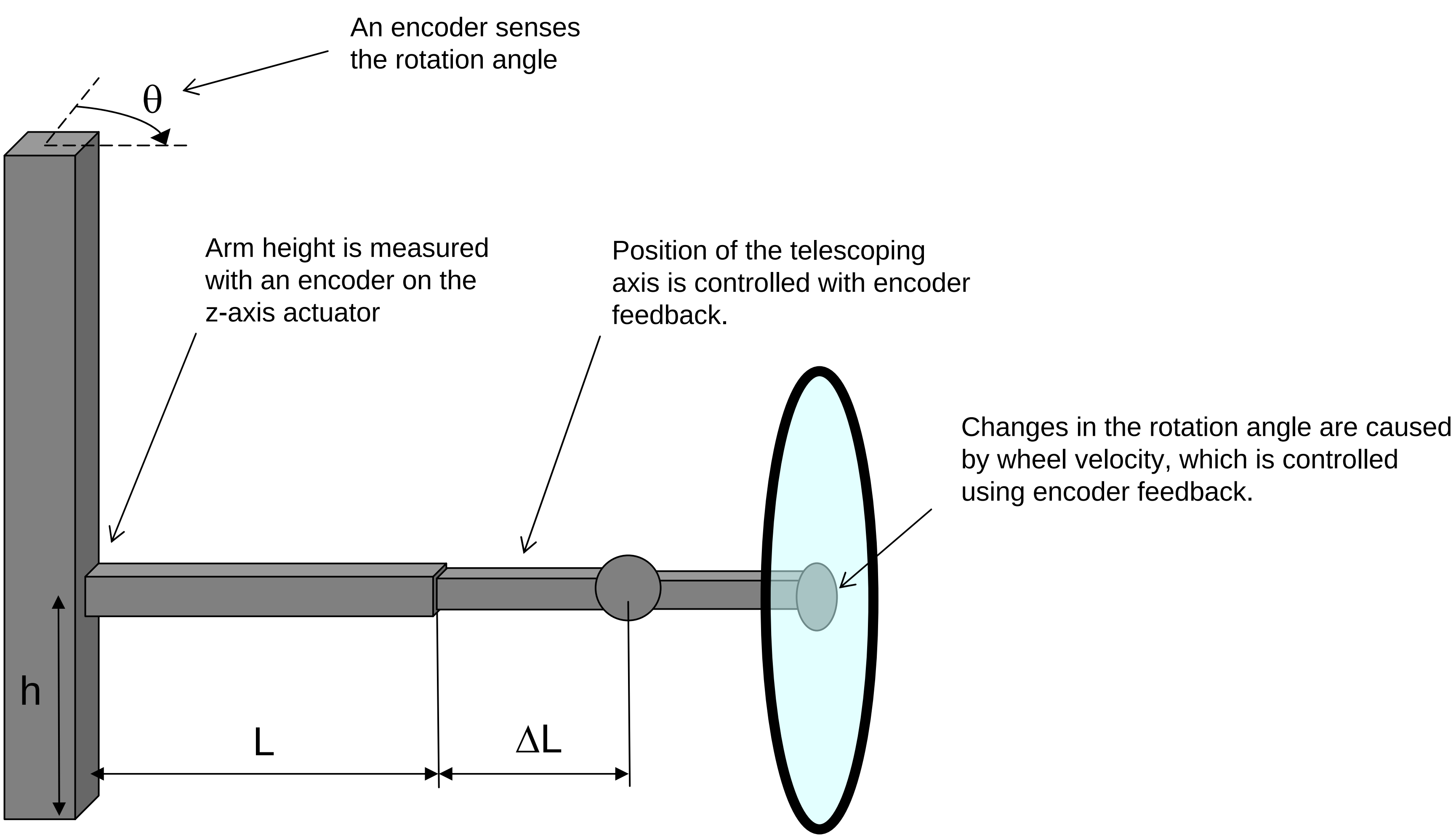




Testbed Actuation



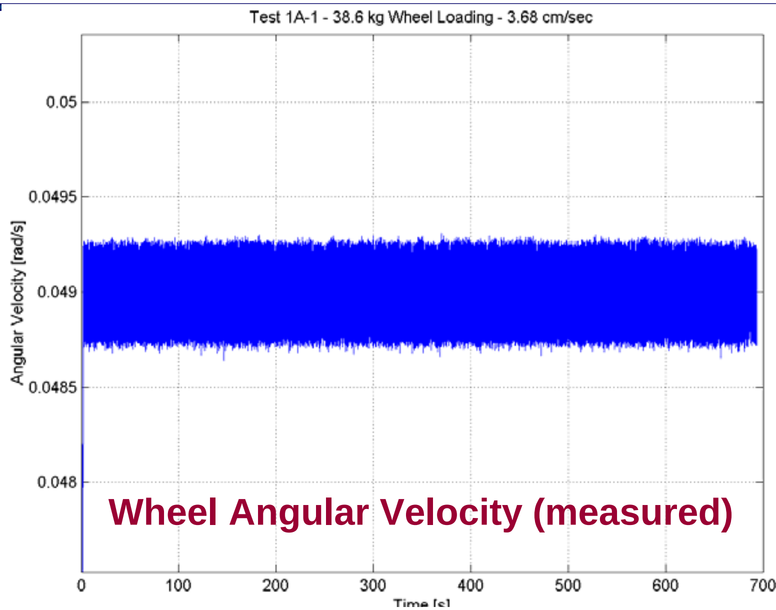
Sensing

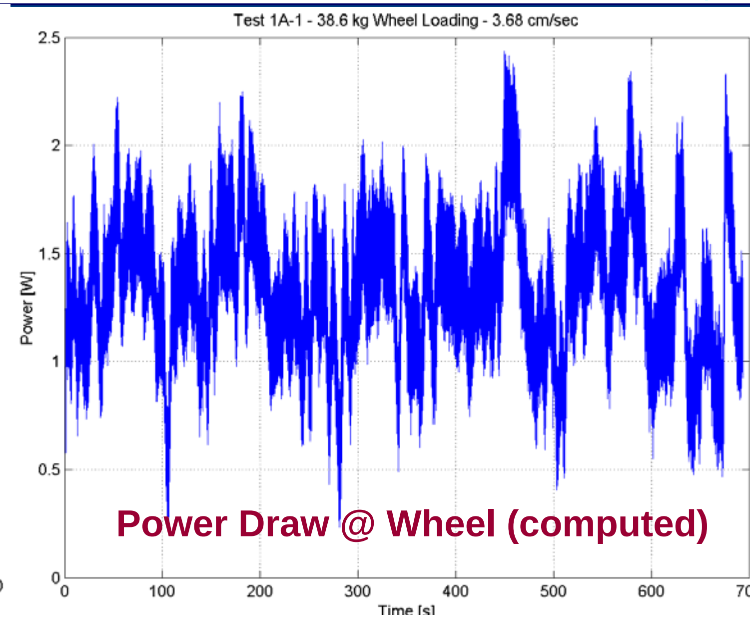

An encoder senses the rotation angle
θ
Arm height is measured with an encoder on the z-axis actuator
Position of the telescoping axis is controlled with encoder feedback.
Changes in the rotation angle are caused by wheel velocity, which is controlled using encoder feedback.
h
L
ΔL

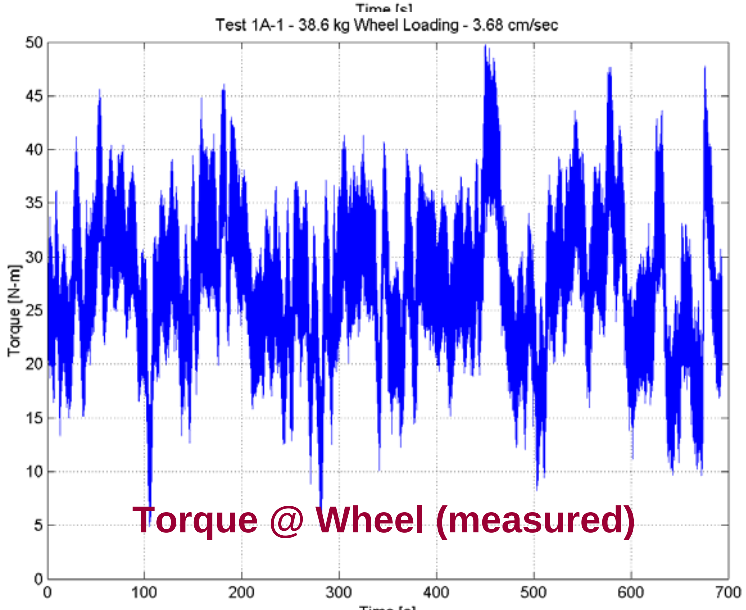
Mobility Experiments

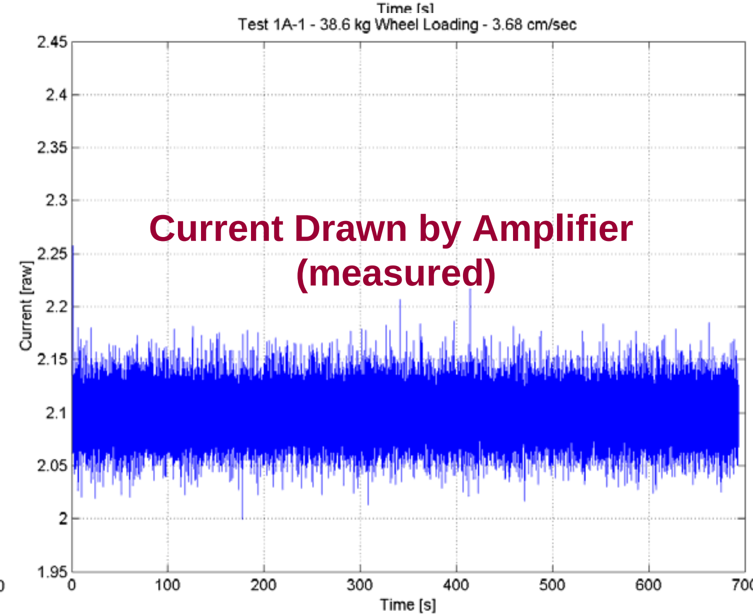
- **Variables**
  - Material Composition (various types of sand, Mars simulant)
  - Depth of Lose Soil Layer (1”-6”)
  - Terrain Geometry (flat, sloped, obstacles, combined)
  - Wheel Rotational Velocity (~3.5-60 cm/s)
  - Wheel Loading (~40-70 kg, may go as high as 100 kg)
  - Rim Material (Polyethylene, Kevlar, Vectra)
- **Sensed Values (currently)**
  - Output Torque
  - Total Electric Power Draw
  - Current Draw into Amplifier
  - Knee-joint Angle
  - Wheel Rotational Velocity

Typical Results



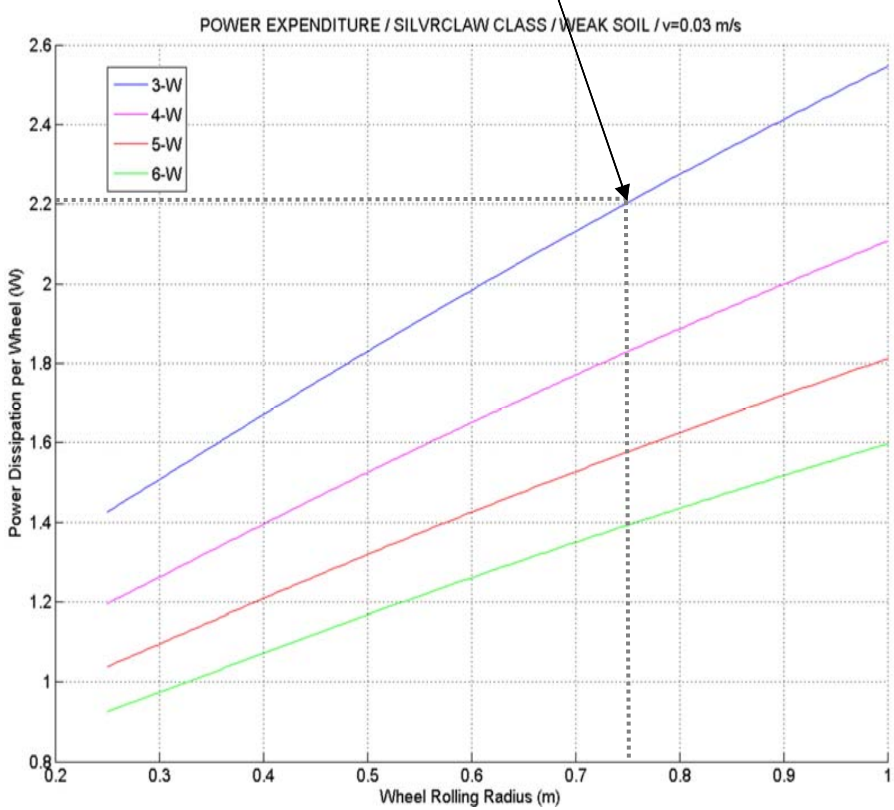




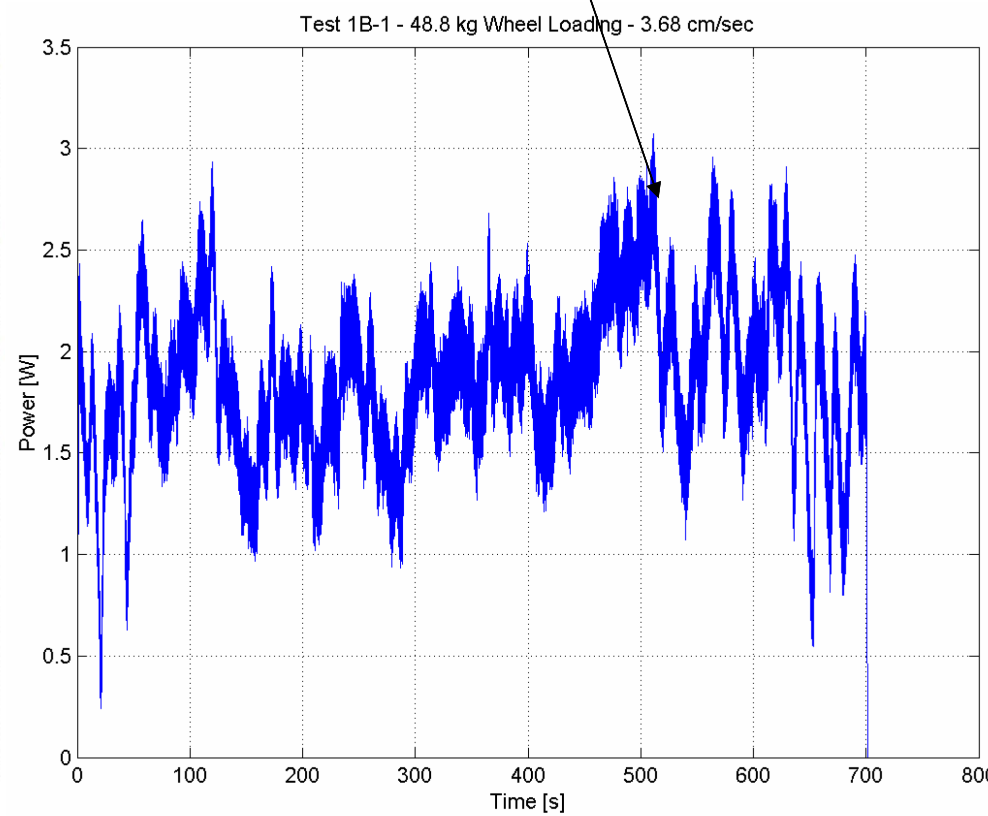


Projected vs. Actual (example)

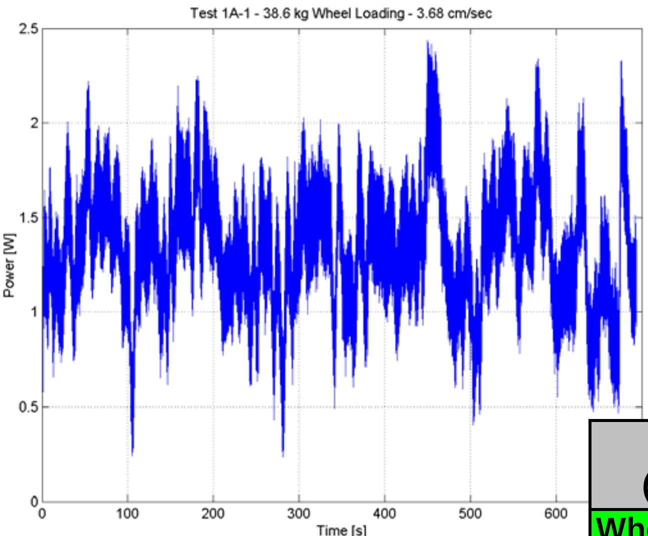
Estimated ~2.2 W per wheel
150 kg 3-wheeled rover / ~50 kg/wheel
0.75 m rolling radius SILVRCLAW
Martian soil: c= 1 kPa, ϕ= 18 deg

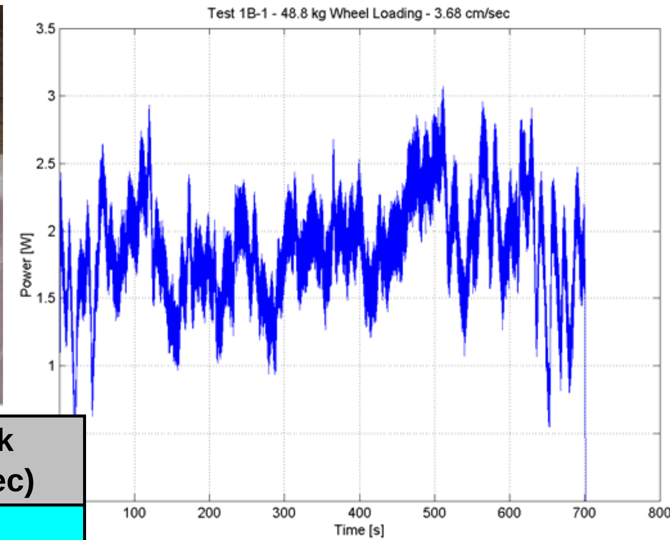


Estimated ~2.2 W per wheel
Wheel Loading: 48.8 kg
0.75 m rolling radius SILVRCLAW
Mix of fine silica sand (c<2 kPa, ϕ= 25-30 deg)

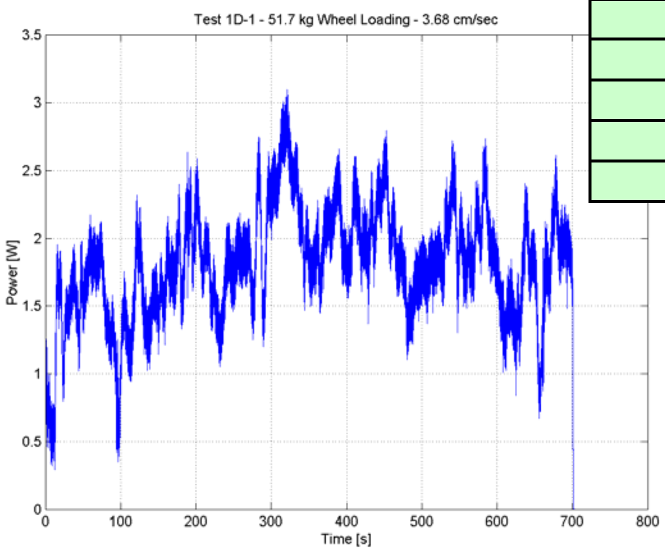


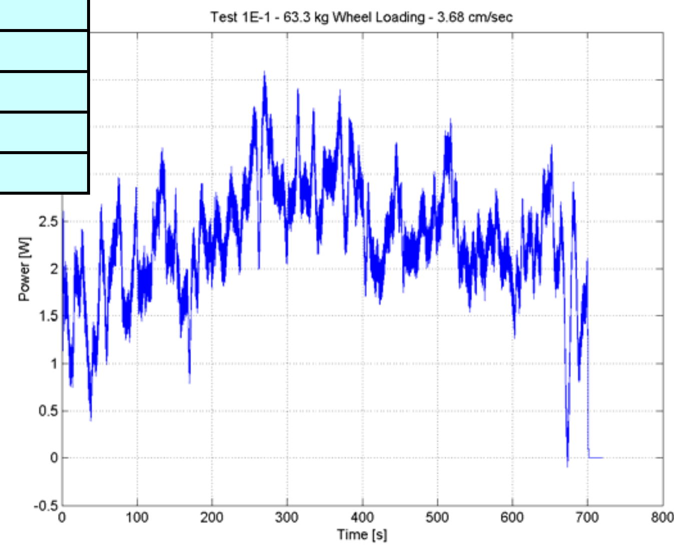
Power Draw vs. Loading





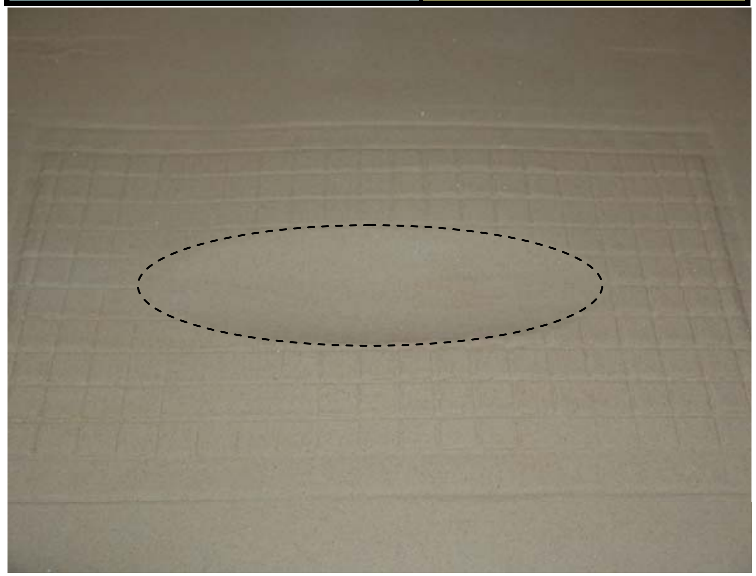
Average Power Dissipated in Soil Work (all values for ground speed: 3.68 cm/sec)	
Wheel Loading (kg)	**Power (W)**
38.6	1.40
48.8	1.75
51.7	1.85
59.6	2.25
63.3	2.35

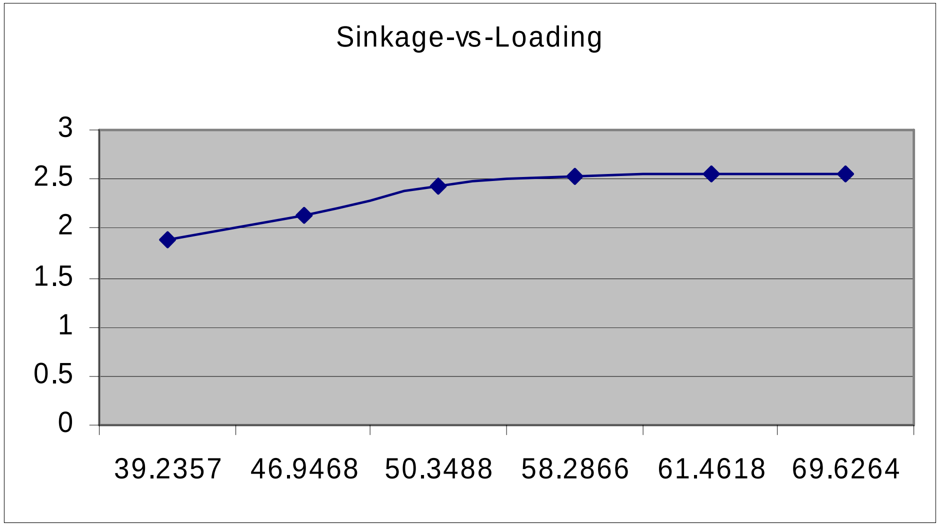


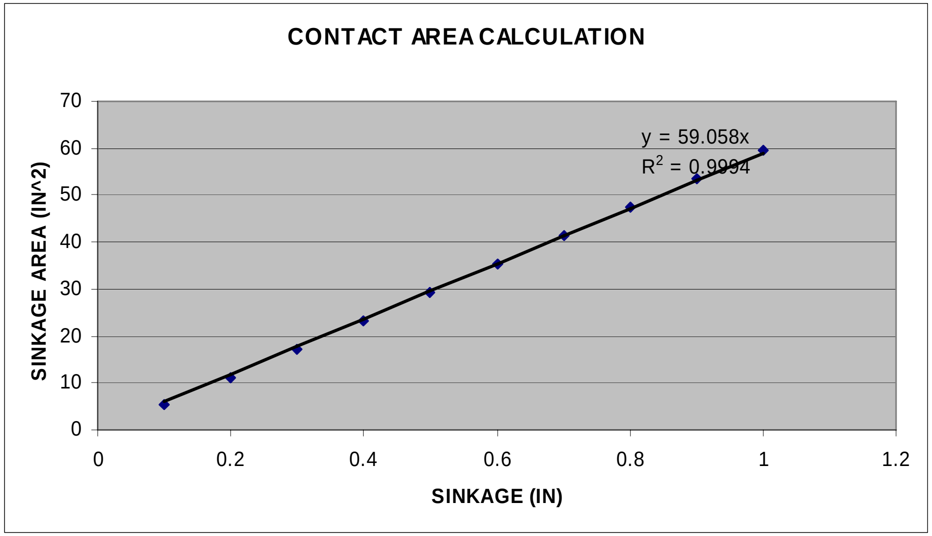


Wheel Sinkage (Static Experiments)

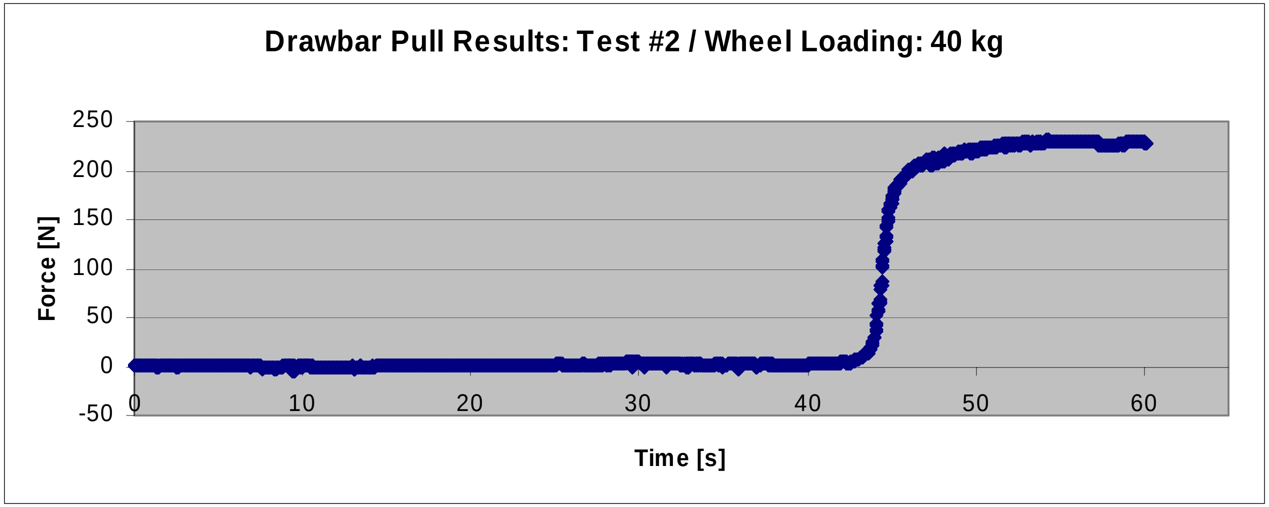
Wheel Loading (kg)	Sinkage (cm)
39.2357	1.88
46.9468	2.13
50.3488	2.44
58.2866	2.54
61.4618	2.55
69.6264	2.56





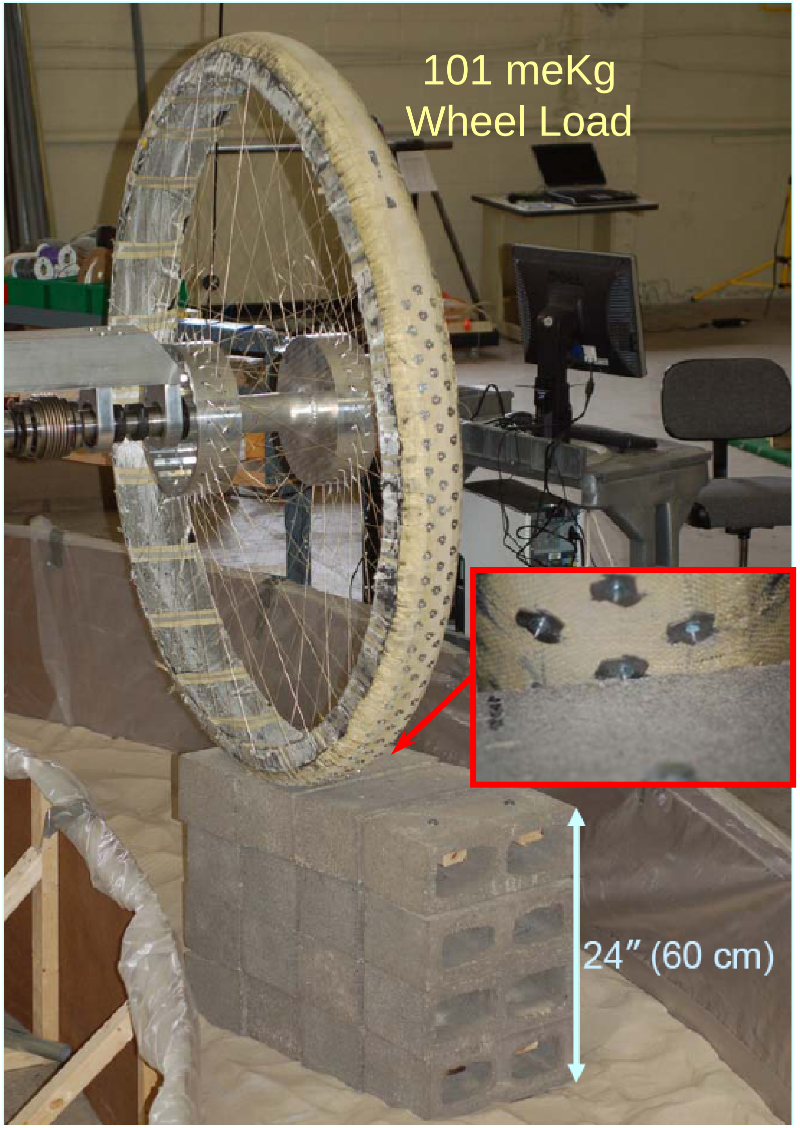


Drawbar Pull

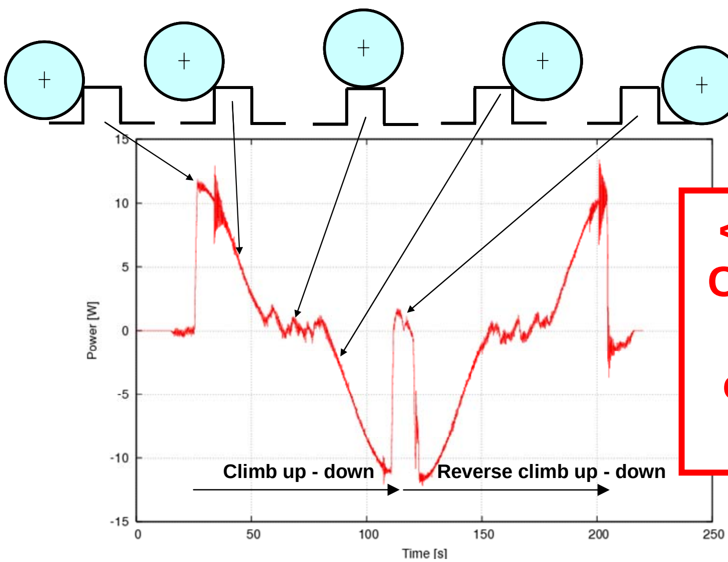


First results indicate excellent drawbar pull of ~60% of wheel loading at contact patch (results are practically independent of wheel loading).

Extreme Obstacle Testing – Orthogonal Obstacle Climb



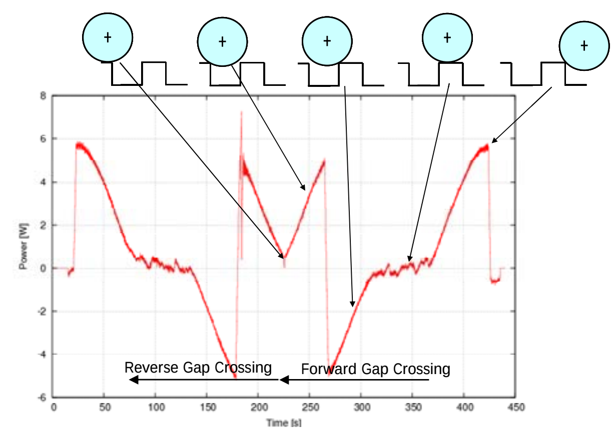
- **Conducted experiments with 6", 12", 18", and 24" orthogonal blocks**
- **Proved theoretical obstacle climbing of single powered wheel (40% of wheel diameter assuming high friction >1 wheel/surface contact)**
- **Single spoke contact sufficient to carry 101 meKg wheel over obstacle. No spoke or rim failures occurred.**



<12W Power Consumption for 3cm/s climb at 101 meKg

Extreme Obstacle Testing – Negative Obstacles

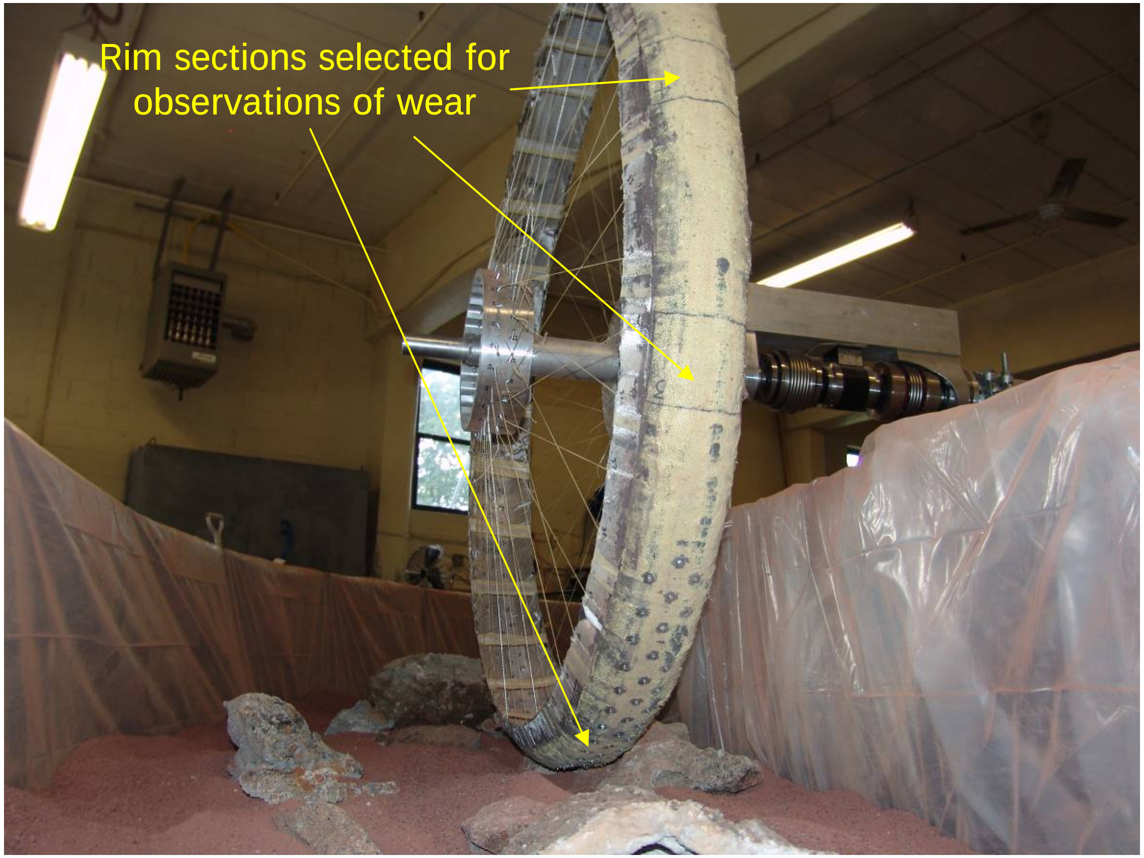
- **Conducted experiments for gap widths of 24” and 48”**
- **Proved theoretical limit of single wheel gap crossing capability of 80% of wheel diameter**
- **Combined orthogonal obstacle climbing and gap crossing**



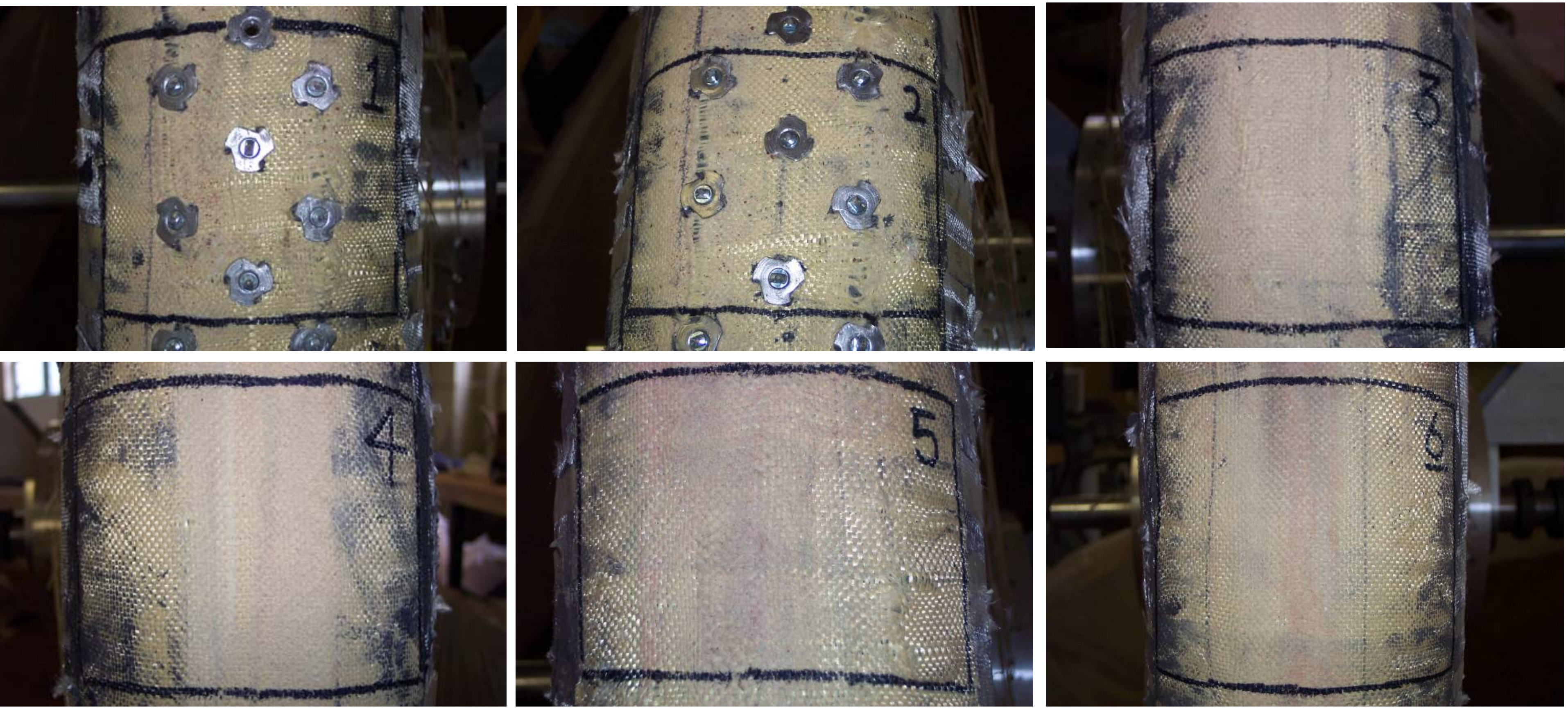
~46″ (1.2 m) gap; theoretical limit for wheel gap crossing

Endurance Tests

- **Studied rim material abrasion resistance through prolonged endurance runs**
- **Observed visible wear on rim material**



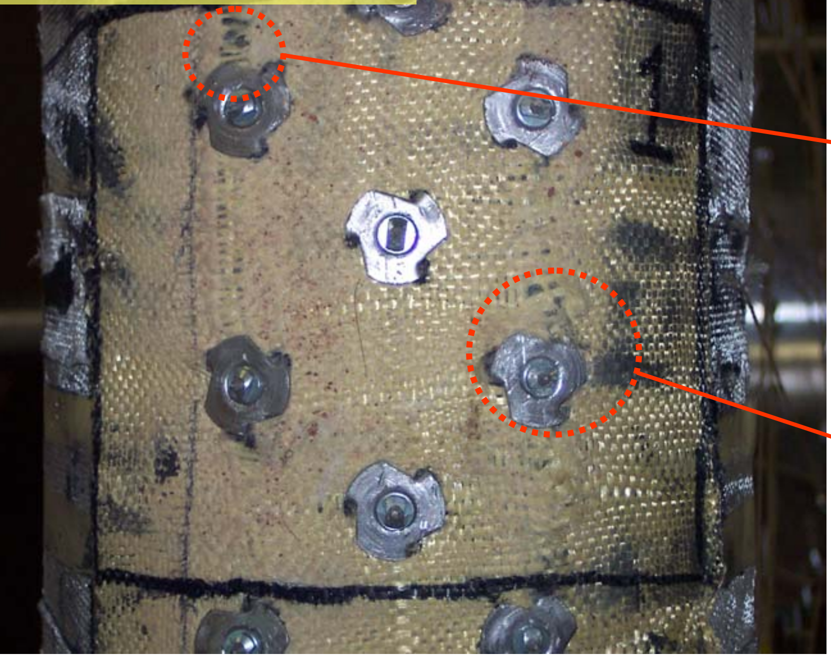
Rim Reference Sections

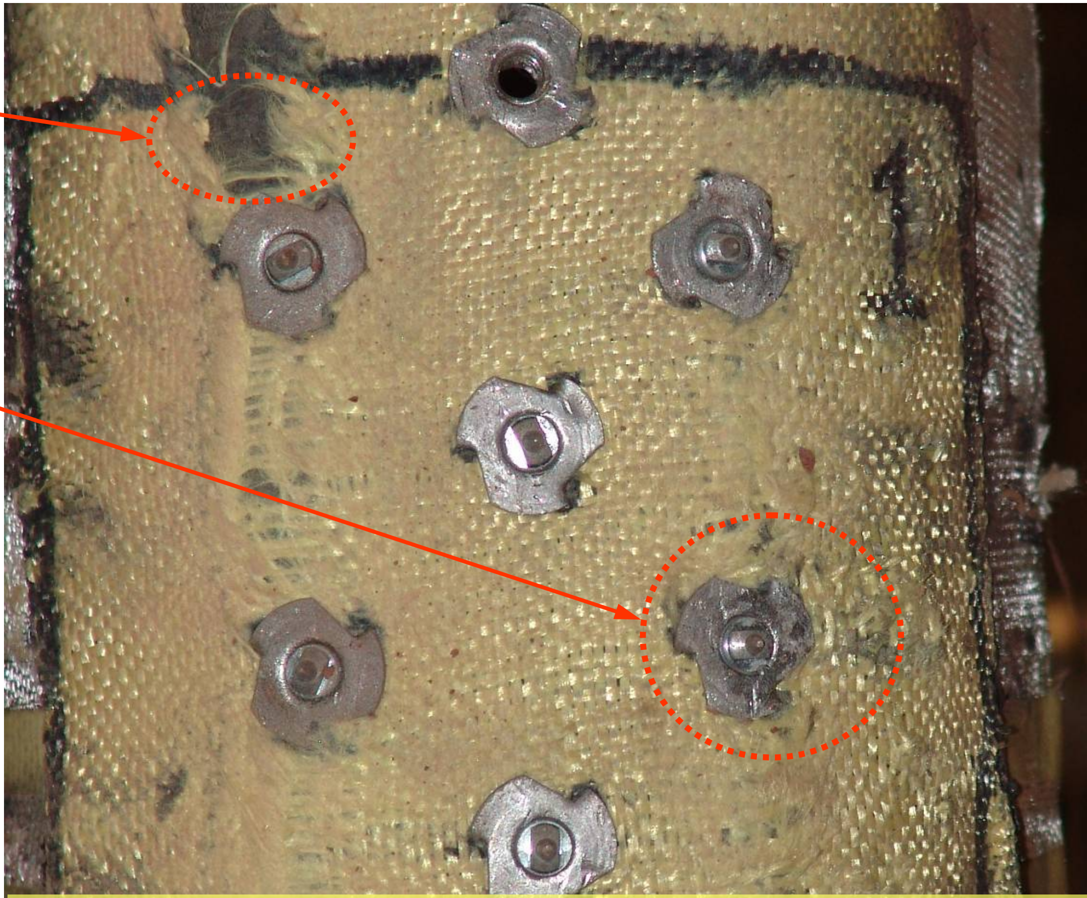


Before starting the endurance tests we selected 6 sections on the rim to study wear effects. Those sections were relatively free of wear from previous tests.

Rim Material Wear – Section 1

Before endurance tests





After 7 km of endurance tests.
No visible wear on either smooth areas or around cleats.

Mobility Test Summary

15 experiments – flat & rolling terrain traverse
Mars equivalent mass: 100 kg
Used fine sand (< 1 kPa cohesion, ~ 30 deg internal friction); excellent Mars soil simulant
Max speed: 80 cm/sec (28.8 kph), Min speed: 3.7 cm/sec (1.37 kph)
Ave. power for max. speed traverse: 15 W
Ave. power for min. speed traverse: 0.7 W

2 experiments – Gap crossing & step climb
Tested on 24” (60 cm) & 48” (1.2 m) gaps
Forward speed: 1.48 cm/s
Ave. power to climb gap wall: 5 W

23 experiments – Consecutive & individual steps
Tested on 6”, 12”, 18” and 24” orthogonal steps
Climb speeds for 6” step: 3.8-14.7 cm/sec
Climb speeds for 12”/18”: 1.48-3.8 cm/sec
Max. power to climb 24” step at 1.48 cm/s: 6 W
Max. power to climb 18” step at 3.8 cm/s: 12 W

Mars Landscape Test Statistics

20-cm boulder climb
Max power at 3 cm/s: ~9 W
Max power at 12 cm/s: ~40 W
Max torque at 3 cm/s: ~230 N-m
Max torque at 12 cm/s: ~250 N-m

30-cm mound climb
Max power at 3 cm/s: ~7 W
Max torque at 3 cm/s: ~180 N-m

MARS2 tests
Max power at 3 cm/s: 2-3 W
Max torque at 3 cm/s: 40-70 N-m
Max power at 6 cm/s: 3-3.5 W
Max torque at 6 cm/s: 40-45 N-m
Max power at 9 cm/s: 5-6 W
Max torque at 9 cm/s: 40-50 N-m

MARS2+crushed basalt tests
Max power at 3 cm/s: 2-3 W
Max torque at 3 cm/s: 45-80 N-m
Max power at 6 cm/s: 4-4.5 W
Max torque at 6 cm/s: 50-55 N-m
Max power at 9 cm/s: 4.5-7 W
Max torque at 9 cm/s: 40-55 N-m

Basalt boulder patch tests
Max power at 3 cm/s: 7 W
Max torque at 3 cm/s: 180 N-m
Max power at 6 cm/s: 15 W
Max torque at 6 cm/s: 190 N-m
Max power at 9 cm/s: 22-25 W
Max torque at 9 cm/s: 190-210 N-m

Drawbar pull voltages from Stu ranged from 2.6 to 3.3 V, which corresponds to 52 to 66 lb-force (or 231 to 294 N)

Rim Material

- **Tested, Evaluated, and Downselected Method for Rim Thermal Deployment**
- **Conducted Material tests on coupons – 5 times stiffer elastic modulus than original conservative proposal estimate = 3-5 times gain in spoke deployment strain margin**

"Deployed" Rim Coupon

Rim Thermal Deployment Coupons w/ Integrated Wire Heater

Pull Test Coupons

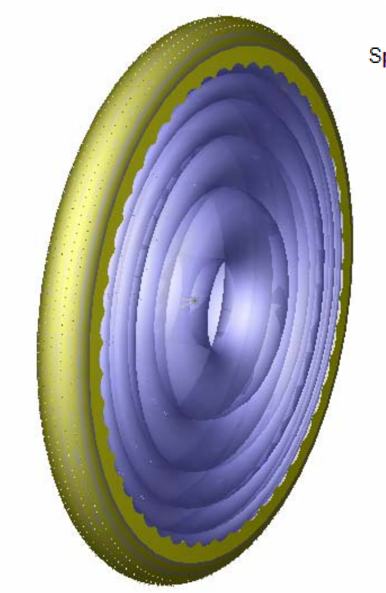
Infaltion/Bagging System Development

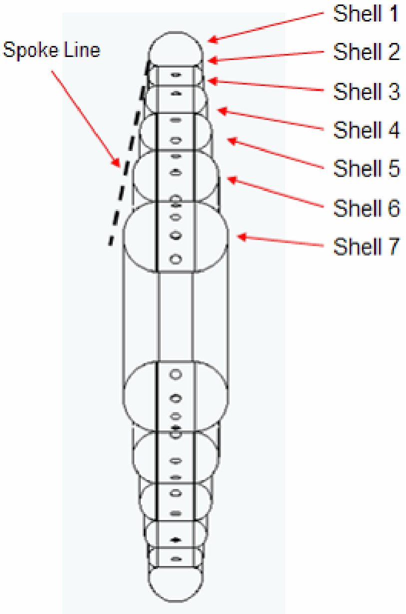
- **Developed and tested thermally deployable composite with low brittle transition temperature for deployable SILVRCLAW exoskeleton**
- **Developed inflatable wheel deployment system for deploying SILVRCLAW exoskeleton wheel structure**

Shell 7/Hub

Deployable Exoskeleton Composite w/ Embedded Heating System

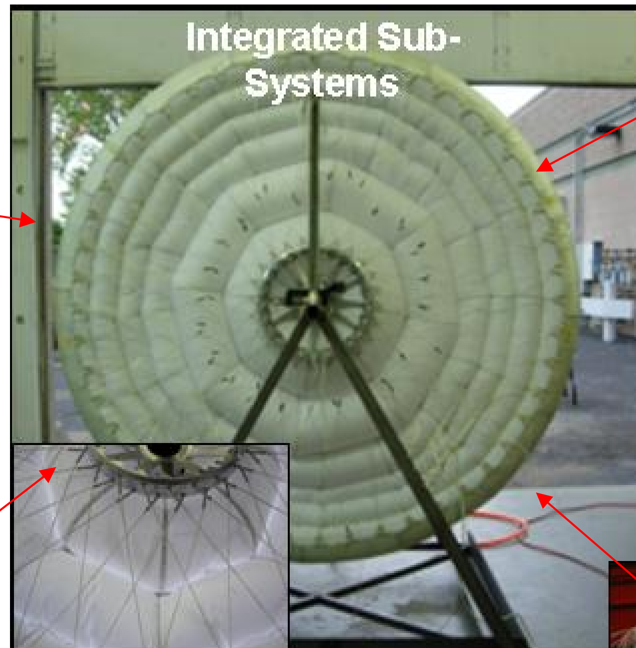
Inflatable Prestrain Deployment System





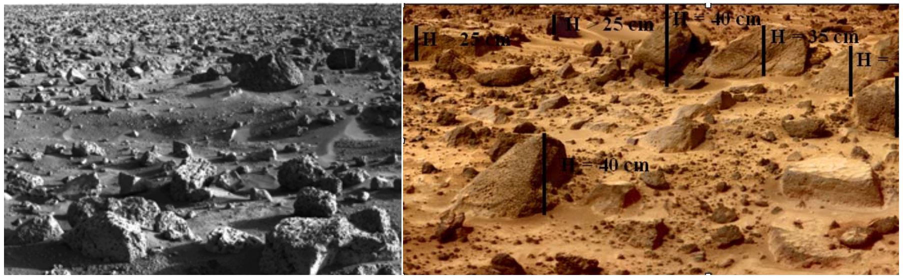
Structural Integration & Deployment

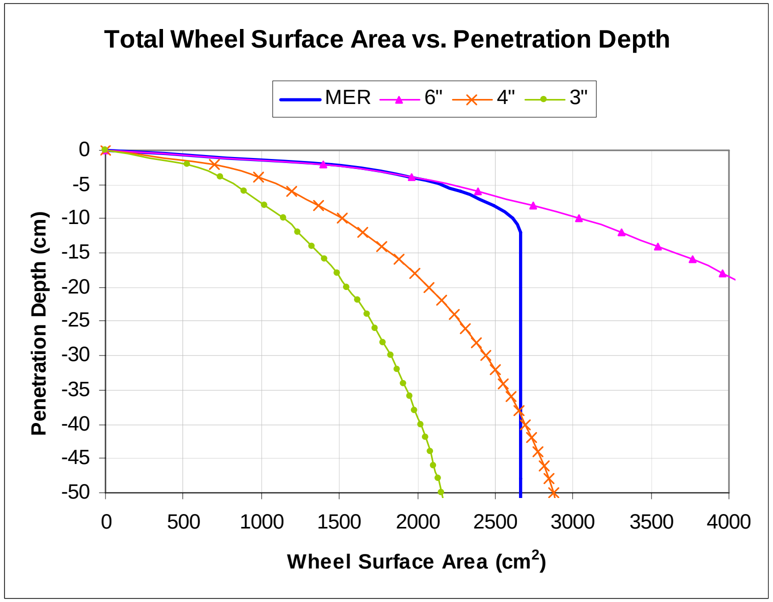
- Integrate Sub-Systems into Deployable Rim Design
- Testbed Test Deployable SILVRCLAW Wheel

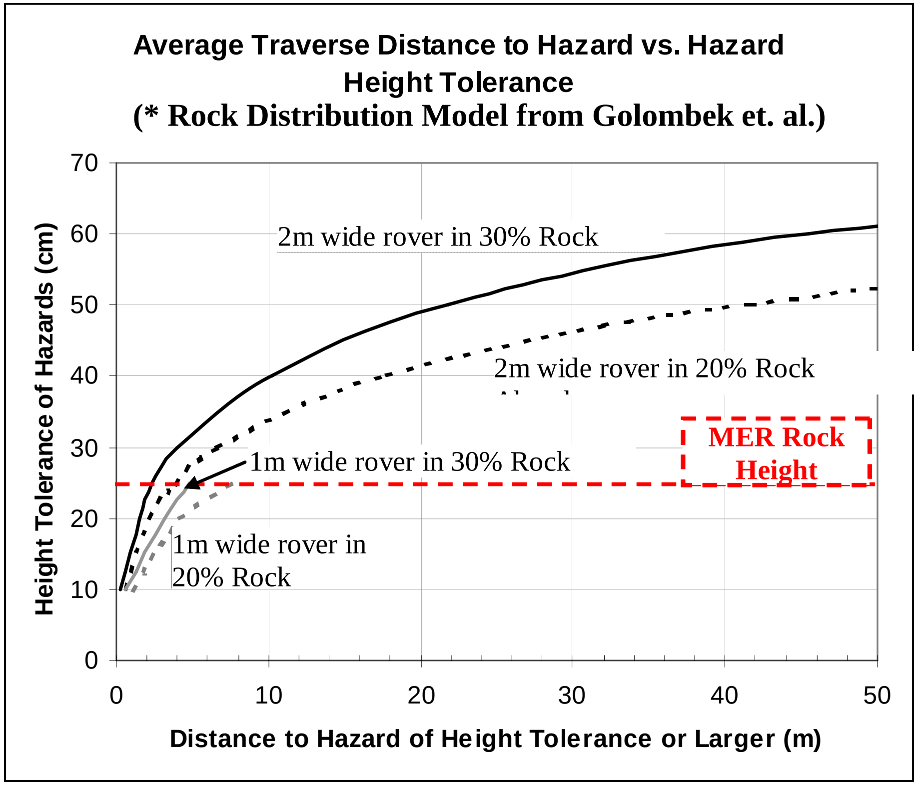


SILVRCLAW Wheel Sizing

- **Identify geometry requirements for a large diameter deployable wheel**
  - 1.3-1.5m diameter specified based on ground clearance estimates, orbital imaging resolution (MRO’s 30cm/pixel), drive power estimates, and some tolerance to manufacturing
  - Initial 6” (15cm) wide rim selected based on 1st order equivalent footprint sinkage rates relative to MER wheel profiles







Mobility Experiments

- **Variables**
  - Material Composition (various types of sand, Mars simulant)
  - Depth of Loose Soil Layer (1”-6”)
  - Terrain Geometry (flat, sloped, obstacles, combined)
  - Wheel Rotational Velocity (~3.5-60 cm/s)
  - Mars Equivalent Wheel Loading (~102-184 kg, may go as high as 250 kg)
  - Rim Materials (Visually evaluated for wear after endurance runs)
- **Sensed Values (currently)**
  - Output Torque
  - Total Electric Power Draw
  - Current Draw into Amplifier
  - Knee-joint Angle
  - Wheel Rotational Velocity

Anticipated SoA Improvements and Mission Relevance

- **What is the anticipated performance/capability improvement of this task as compared to the state of the art?**
  - Ability to deploy wheels ~1.5m diameter for providing low hazard density (<1 hazard per 100m) and waypoint placement from orbit (i.e. with MRO's Highrise 30cm/pixel resolution)
  - 10-100 fold increase in the load carrying capability of inflatable wheels (i.e. >100kg per wheel in Mars gravity field).
  - Low power traverses
    - <100 Whr/km per wheel
    - <10W/wheel for >1km/sol traverses.
  - No requirement for sustained gas pressure over the duration of wheel operation (for deployment only)
  - Minimal number of mechanisms
- **Which mission will potentially benefit from this?**
  - Mars Scout – Long range, aggressive terrain, surface payload capacity, compactly stown for flight on low cost Delta II or Falcon class launch vehicles.
  - NASA Flagship – Astrobiology Field Lab – Long range, heavy science payloads capable of accessing sedimentary terrains, high rock density, cratered terrains in paleo-lakebeds, polar layered deposits, etc…

SILVRCLAW Traits for Robotic Mobility

- **Encourages simpler kinematic designs and motion control schemes**
- **Suspension may not be required**
- **Offers flexibility to design a rover that surmounts rather than circumnavigates.**
- **Enable aggressive traverses over large negative obstacles (up to ~1.2m)**
- **Encourages designs with less overhead on sensing and navigation software-associated processing**
- **Offers truly a simple locomotion solution for long-range autonomous navigation in extreme terrains**